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REVIEW OF THE K-65 SILOS STUDIES FOR THE FMPC APRIL 1, 1991

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Review of the K-65 Silo Studies for the Feed Materials Production Center at Fernald Ohio

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1.0 Introduction

The four concrete waste storage silos at the Feed Material Production Center (FMPC) have been the subject of several recent studies [1-3]. On March 18,1991 the Engineering Analysis Division 1544 of Sandia National Laboratories was asked to conduct a review of the information published to date. These documents include several structural analyses, material test results, a probabilistic risk assessment and correspondence between the Environmental Protection Agencies of the U.S. and Ohio (EPA and OEPA), the U.S. Department of Energy (DOE) and the Westinghouse Materials Company of Ohio (WMCO). Considering the extensive effort that went into the development of the structural models and the risk assessment, a detailed review of these documents was not possible in the given time. Rather, efforts have been concentrated on reviewing specific aspects of their findings. The tasks assigned to this review team were:

(1) Perform a critical review and evaluation of existing reports on the subject of storage silo response to abnormal environments and the environmental consequences of silo damage.

(2) Provide an opinion regarding the advisability of constructing an over-structure to aid in ore residue containment.

(3) Visit the Fernald site for an inspection of the silo structures and for technical interchange with on-site staff.

(4) Provide this report of our findings and recommendations by April 1, 1991.

Our efforts have been concentrated on the following specific concerns:

What is the failure mechanism for the concrete domes? Camargo Associates, Limited and Bechtel National Inc. have performed linear structural analyses using both normal service loads and abnormal environment loads to predict the onset of silo failure. In this report we investigated the nature of a dome failure due to tornado loads.and reviewed the previous calculations for completeness.

Is the transport of residue in a tornado a credible event? This effort was undertaken to quantify the amount of material which could be dispersed in high wind conditions, consistent with a tornadic event.

Is the installation of a bentonite clay layer an appropriate action to reduce radon emissions into the head space of the silos? Further, is the amount of bentonite called for in the corrective action plan the right amount?

Were environmental hazards treated properly in the risk assessment?

Should a structure be erected over the silos? What is the function of this structure?

The remainder of this report will provide a brief history of the K-65 and metal oxide storage silos, discussion of our areas of concentration followed by conclusions and recommendations.

2.0 Background

The concrete storage silos at the FMPC were constructed in 1951 and 1952 to dewater and store high-grade pitchblende ore residue and metal oxide. Silos 1 and 2 contain the K-65 residue and are referred to as the K-65 silos. Silo 3 contains metal oxide and silo 4 has not been used. The silos were filled in the late 1950's.

In 1963 deterioration was observed in the concrete and post tensioning wires of silos 1 and 2. In 1964. their short-crete coatings was repaired, waterproofing material was applied and an earthen berm was constructed around the silos. The berm was built to provide confining pressure lost due to damaged post tensioning wires, protect the tank from further weathering and reduce radon emission. In 1979 the roof vents were sealed. The berms were enlarged in 1983 to prevent erosion.

The first structural analysis of the silos in their degraded condition was performed in 1985 by Camargo Associates, Limited (Camargo). Their study [1] concluded that silos 3 and 4 were still in good condition and capable of serving their design function. It was recommended that the tank walls be sealed against the elements and the design life was predicted to be approximately twenty years. Silos 1 and 2 on the other hand were found to be in considerably worse condition. Many cracks and spalled areas were found in the silo walls. The projected life expectancy of the silo walls and slab was a maximum of five to ten years. However the domes of both silos were found to be structurally defective with no life expectancy. Recommendations were made to remove and dispose of the K-65 residue while providing interim support for the unsound regions of the domes. In 1986 dome covers were placed over the center portion of each dome. Waterproofing foam was applied to the domes and covers in 1987.

In July and August of 1989 a DOE Tiger Team visited the FMPC. One of the teams findings was the potential structural failure of the K-65 silos. As a result, Bechtel National Inc. (BNI) was assigned the task of performing further tests and analyses.

The objectives of this new effort were to:

> Verify the Camargo results and estimate the current state of structural integrity.
>
> Determine the actual properties of the concrete in the silos
>
> Provide a qualitative assessment of the risk of structural failure of the silos.

The conclusions of the Bechtel investigation [2], essentially agree with those of the Camargo report. Material test show that the concrete in the dome of silo 4 has retained less than 30 percent of its original 28 day compressive strength while the walls have retained less than 40 percent. The size of reinforcing bars found in the core samples did not agree with those shown on the construction drawings. Bechtel concluded that the dome covers recommended by Camargo were not required but did not have to be removed.

It should be noted that concrete core samples were taken from silo 4, one of the silos said to be in good condition in the Camargo study. As an argument for using the material properties obtained from these samples the Bechtel report points out that all 4 silos were constructed in the winter months and have been exposed to the same weather conditions for most of their lifetimes. However this is not consistent with the Camargo observation that silos 1 and 2 are in significantly worse condition than silos 3 and 4.

In November 1990 A Probabilistic Risk Assessment for the K-65 Silos at the FMPC was published [3]. Two acute exposure scenarios and one chronic scenario are discussed. Acute Case 1 presumes the release of radon gas and solid residue during a tornado. Acute Case 2 assumes the dome fails spontaneously, releasing radon gas into a low wind environment. The chronic release case is the existing condition. "The results of this risk assessment clearly show that the total risks for the scenarios considered indicate the significance of the threat of release and exposure from the material in the K-65 silos. The chronic radon emission and the potential for acute release of the the radon contained in the head space are probably the more important since the likelihood of these events is either one or close to one. The acute release of residue material has a sufficiently small probability of occurrence that the risk can be considered to be the lesser of the three scenarios but is by no means insignificant."

3.0 Dome Failure

In this section we will discuss the failure of the silo domes due to the pressure differential caused by a tornado. The two tornado pressure loads used in [2] are 401 psf pressure on the outside of the domes and 432 psf suction pressure. Both the Camargo and the Bechtel reports predict that the dome stresses will exceed allowable levels under these loading conditions. We agree that the tornado loads will cause the dome structure to crack and perhaps experience structural instabilities. With respect to the release of radon gas in the head space this can reasonable be construed as complete failure of the dome. However if the scenario being postulated is the dispersal of silo contents then a much more significant structural failure must have occurred. Specifically the dome must have been removed from the silo. Considering this possibility the following simple reasoning is followed. Remote from the wall to dome transition the dome will carry the internal pressure load in membrane stress. This membrane stress is easily calculated. The radius of curvature of the dome is 1085 inches. If we assume all the load to be carried by the concrete an internal pressure load of 3 psi (432 psf) causes a membrane stress in the dome of 202.5 psi.tension. For the concrete of silos 1 and 2 this would cause cracking failure. If the entire pressure load were to be carried by the reinforcing steel the stress in the steel would be approximately 16,200 psi, well below the yield stress. The question now becomes; Can the reinforcing steel develop this stress without pulling out of the concrete. According to section 12.2.2 of the ACI Standard 318, the development length for 1/2 inch reinforcing rods in 1300 psi concrete is 6.65 inches. The overlap between the roof reinforcing mat and the rebar in the wall section is approximately 48 inches. It is therefore unlikely that a suction pressure of 3 psi could remove the dome from a silo. The additional load on the dome due to aerodynamic lift is small compared to the pressure load (approximately .3 psi equivalent suction pressure). In view of the preceding discussion, this would not result in the removal of the dome.

For the case of 3 psi over-pressure the compressive stresses in the dome would exceed the allowable levels discussed in [2] and the structural stability of the dome could not be assured. If the dome were to buckle under this load it would collapse inward, perhaps onto the residue (or the bentonite coating, if it has been installed).

The presence of a badly damaged or even collapsed dome does provide a protective cover for the residue. Scouring of the residue by high winds would be considerably reduced from that assumed in the risk assessment. Since the risk factor due to radon emission is considerably higher than that due to residue dispersal, these considerations are not particularly significant to reducing the risk associated with the existing condition. However, if a radon barrier is installed which effectively reduces the radon in the head space, then the potential dispersal of residue may become the dominant threat.

In an effort to predict the collapse response of the silo, an axisymmetric model of the dome and side wall has been developed.

This model includes the top four feet of the silo wall and the dome. Effects of the earthen embankment on the wall section are neglected.

Concrete properties consistent with the test results found in Appendix C of the BNI report [2] were input to the model. An elastic modulus of 1,300,000 psi and a compressive strength of 1300 psi were used. The concrete was modeled as an elastic perfectly plastic material with the elements being removed if the equivalent plastic strain exceeded .0015 or the effective pressure in the element reached 130 psi tension. This allows the model to capture the development of cracking and crushing of the concrete. It is not the intent of this calculation to predict the exact location of large scale cracking or to find the precise load at which this occurs. Rather it is intended to show the response of a dome made of brittle material with ductile reinforcing to a pressurization event which causes the brittle component of the dome to fail.

An internal pressure load of 3 psi was applied in .03 seconds, held for .03 seconds and removed over .03 seconds. The reduction of the load is intended to simulate pressure equalization through cracks in the dome. This provides a pulse loading with a frequency of approximately 5.5 Hz. This is in the range of structural frequencies reported in the Appendices of the Camargo report [1]. Actual loading times are expected to be longer, on the order of several seconds.

Significant regions of material failure occur at the center of the dome and at the wall to dome junction. This suggests that large scale cracking and spalling may occur in these regions. Figures 1-4 show the progression of material failure in the wall to dome transition region. The development of though wall failure suggests that a circumferential hinge may develop. This could cause a plunging failure of the dome. Analysis of this condition beyond through wall concrete failure is not appropriate with this model. Numerical, artificial stiffness would be introduced and the results would not be reliable. A more refined model, capable of capturing further collapse behavior would be quite expensive. Given the substantial uncertainty in material properties this additional effort is not considered useful.

The analyses presented here should be viewed as qualitative. Thorough treatment of this problem was not possible in the time allowed. However, the findings discussed here coupled with the inherent ruggedness of reinforced concrete structures alluded to in

[2], form the basis of our opinion that the domes will not be removed by a tornado.

In concluding the structural portion of this report the following comments are offered regarding the seismic analysis performed by Camargo.

There is not sufficient information in the documents we reviewed to make a judgement regarding the treatment of earthquake loadings. The PRA [3] contains a very brief statement dismissing an earthquake as an initiating event. This may be based on the conclusions of the Camargo report [1]. However, the statements on pages 7 and 33 of the Camargo report are disturbing. They are: " the dome being relatively non-rigid, would move with the ground motion with no resultant large stress increase and consequently would not suffer any additional distress" and, " Based of the results given in Appendix F, the dome is not stiff enough to resist movement. Therefore, the domes will move along with the ground motion induced by the synthetic earthquake." No structure, regardless of its stiffness can resist the motion of its foundation. Very stiff structures tend to move with their foundations and experience very little dynamic amplification of the ground motion. Flexible structures on the other hand can experience accelerations significantly higher than the ground motion. Structures with very low natural frequencies, such as high rise steel framed buildings, can "ride out" an earthquake without transmitting the strong shaking motion to the upper portions of the structure.

Earthquakes typically have motions with high energy content in the frequency range of 2 to 8 Hz. The natural frequencies tabulated in the Appendices of the Camargo report show five natural frequencies between 5 and 12 Hertz. The mode shapes associated with these natural frequencies do not appear to be included in the information we received, so it is difficult to speculate on the dome response to earthquake loads.

Vertical ground motion is not treated. Depending on the nature of the earthquake, the location of the epicenter and the subsurface geology, earthquakes can have a significant vertical component. In the time permitted in this review, independent assessment of earthquake response is not possible. However, the discussion of conclusions in the Camargo report suggest that further review and/or clarification is in order.

Regardless of the rigor with which Camargo addressed earthquake loads, their impact on the risk of dome collapse is probably not significant. This is not to imply that the domes would survive an earthquake, but rather reflects the conclusion that spontaneous dome collapse under normal service loads is a credible event. The principle concern with the accuracy of the earthquake analysis is the possibility that other failure scenarios may exist. One such scenario is pointed out in the executive summary in Appendix D of the Camargo report (soil liquifaction). As recommended by Camargo, "this condition should be examined by a qualified geotechnical engineer."

4.0 Residue Dispersal

This section provides an estimate of the loss of radium-laden granular material from a K-65 silo as a result of strong winds during a tornado. The silo is a cylinder with a diameter of 25 m, and the dome which normally covers the silo is assumed to have been completely removed by tornado. The material within the silo has a radium concentration of 375 nCi/g, a density σ = 1600 kg/m^3, and particle sizes over a large range with 13% of the material having a diameter of less than 0.003 mm [3]. A previous estimate of the mass loss during a tornado was given in [3] for the purposes of a probabilistic risk assessment. The purpose of the present effort is to obtain a more accurate and physically motivated estimate of the mass loss for use in efforts to reduce loss of radium in the event of a tornado.

In [3], it was estimated that the first 4 feet of material would be removed from the top of the silo by the worst-case tornado. This mass loss was attributed to the pressure drop ΔP across the core of the tornado. For the worst-case tornado [3], ΔP = 3 psi, based on a Rankine vortex model of the tornado core. The 4 ft. estimate was obtained by (incorrectly) equating the pressure drop across the core of the tornado with the hydrostatic pressure of the material at a depth L. That is,

$$\Delta P = \sigma g L$$

is solved for L (= 4 ft.), given ΔP, and σ (g is gravity). It appears that this formulation is motivated by the idea that a tornado exhibits a suction of strength ΔP on the earth, so that materials with hydrostatic pressure less than ΔP will be lifted away from the earth. However, for the Rankine vortex model used to characterize the tornado, the direction of ΔP is parallel to the surface of the earth, whereas the hydrostatic pressure gradient of the material in the silo is perpendicular to the surface of the earth. Thus, in the above relation, forces in orthogonal directions are incorrectly equated. Moreover, there is no upward suction motion in the Rankine model of the tornado, as implied in [3]. Also, the approach used in [3] does not specify the mass removal rate.

The importance of the removal rate can be seen by considering that if a tornado hovered over a silo for a very long time (e.g., many hours), one could be quite certain that much of the material would be removed. It is unlikely, however, that a tornado will remain directly above a silo for longer than a few minutes, so that no suction-type mass removal is expected. A more likely situation is that strong winds (parallel to the surface of the earth) which are associated with a nearby tornado will remove material from the silo. Thus, the approach taken here is to first estimate the mass removal rate due to strong winds. Then, an estimate of the total mass removal can be obtained by multiplying the removal rate by a characteristic residence time of the tornadic winds.

The transport of surface particles by winds is highly complex since it involves the interaction of turbulent flow with particles, and the interactions of many particles. The fluid-particle interactions involve lift and drag on the particles and the lift and drag re-actions on the fluid. Particle-particle interactions (collisions during rolling, hopping, etc.) depend strongly on the motion imparted by the fluid and the geometry of the particles. Each of these phenomena are difficult to characterize, but have been studied in detail. As necessitated by the short time frame of this work, a highly distilled review of the literature in this area is given to motivate a greatly simplified analysis. The seminal work in this area is the book The Physics of Blown Sands and Desert Sands by Bagnold [6], which gives a vivid description of the phenomena, presents many empirical observations, and postulates theories for the phenomena. The two major types of particle transport by the wind are "saltation" and "suspension." According to Owen [7], saltation occurs when "individual particles ejected from the surface follow distinct trajectories under the influence of air drag and gravity. They fail to enter into a suspension, as they would if the particles were very fine or the wind violent:

instead, once lifted from the surface, they rise a certain distance, travel with the wind and then descend, either to rebound on striking the surface or to embed themselves in it and eject other particles." For heavy particles whose density is much larger than the density of air (as in the present case), the principal means of upward particle motion is eddy motions associated with turbulent flows, rather than aerodynamic lift. In saltation flows, the height of a typical particle trajectory is less than 1 meter, whereas in suspension flows, particle heights can easily be tens of meters. Owen's work [7] is the single most important contribution to the theoretical framework of saltation, since he developed solutions for the fluxes of saltating grains in a fully-developed saltating layer; i.e., the layer is not changing in the streamwise direction. An example of more recent work in saltation and suspension can be found in [8], which uses stochastic techniques to simulate more general cases (many particle sizes, different types of trajectories, etc.).

In order to make use of these previous works, the wind-induced phenomena occurring on the surface of the material are postulated and placed in context of the previous work. It is postulated that the layer of moving particles on the surface of the silo material will increase in thickness with streamwise distance across the diameter of the silo. On the windward side of the silo, the layer of participating particles will be very thin; perhaps consisting only of particles rolling over one another. Occasionally, particles will be ejected upward due to a collision with another particle, and begin to saltate. As particles plunge back to the surface, their surface impact will eject more particles even further upward. As this type of process becomes more frequent in the streamwise direction, the saltating layer will increase in a manner similar to a developing fluid boundary layer. This postulated scenario does not coincide precisely with saltation or suspension analyses, primarily as a result of the developing nature of the flow. The basic phenomena, however, appears to be more closely related to saltation, since the thickness of the layer of moving particles is expected to be on the order of a meter, rather than reaching tens of meters as it flows over a distance of one silo diameter (25 m). In addition, bouncing and hopping of particles is believed to be a significant part of the processes, much like saltation. Thus, the solutions for saltation will be used to estimate the particle motion in the silo.

According to Owen, the region in which saltation occurs is

$$0.064 < \tau/(\sigma g d) < 0.1$$

where τ is the total fluid shear stress on the particles (viscous and turbulent shear), σ is the density of the particle, g is gravity and d is the particle diameter. Below the lower bound, no particles are ejected, and saltation does not occur. Above the upper bound, suspension rather than saltation occurs. We shall assume that the particle motion in the silo is described by this range. (Owen states that the upper bound is O(1), but examination of his analysis suggests that a more precise (but still approximate) value is 0.1.) For σ = 1600 kg/m^3, g = 9.8 m/s^2, and $\tau = \rho u_\tau^2$ (ρ is the density of air (1 kg/m^3), u_τ is the shear stress velocity (m/s)),

$$10d^{1/2} < u_\tau < 40d^{1/2} \quad \text{(d in meters)}$$

Thus, for a specified particle size, the shear stress velocity can be computed and used in the solutions provided by Owen for mass flow rate. First, consider the largest particle and shear stress velocity for which Owen provides a solution: d = 10^{-3} m, for which

$$0.28 < u_\tau < 1.20$$

Owen's solution is given as $Gg/(\rho u_\tau^3)$ versus diameter along curves of constant u_τ (G is the mass flow rate per unit width of a plane perpendicular to the flow normal). The largest flow rate per flow width is 1600 kg/(m-hr) (for u_τ = 1.2 m/s and d = 10^{-3} m). For comparison, the lowest saltating mass flow rate per flow width is 0.015 kg/(m-hr) (for u_τ = 1.2 m/s and d = 10^{-3} m). (Lower mass flow rates will not sustain saltation.)

To determine the most appropriate u_τ for use in the analysis, the values of u_τ above are compared with well-known values of shear stress velocity obtained from laboratory experiments (e.g., [9]). For incompressible flow over a flat, smooth boundary, the ratio of freestream velocity U and the (laboratory) shear stress velocity u_* lies in the region [9],

$$20 < U/u_* < 45$$

To compare with the range of U/u_* for saltation, consider tornadic winds of $60 < U < 300$ miles per hour and $u_\tau = 1.2$ m/s. The resulting range is

$$22 < U/u_\tau < 107$$

where $U/u_\tau = 107$ exceeds $U/u_* = 45$ by approximately a factor of two. This is viewed as a relatively good comparison, considering the two flows being compared are considerably different (incompressible flow vs. significant compressible effects for winds above 100 m.p.h., flow over a smooth flat plate vs. flow over a rough, moving sand surface, and laboratory boundary layer data vs. tornadic winds). For $u_\tau = .28$ m/s, the comparison is much poorer; hence $u_\tau = 1.2$ m/s is chosen for use in estimating mass flow rates. Also note that using $u_\tau = 1.2$ m/s will result in the largest mass flow rate in the context of Owen's solutions.

Lacking the time for a more rigorous treatment, the largest mass flow rate per width G = 1600 kg/(m-hr) is assumed to be appropriate for all the material in the silo. Assuming the width of the flow is the silo diameter, 25 m, the mass flow rate is G D = 40000 kg/hr. If the volume of material removed is $L\pi D^2/4$ (L is the depth, D is the diameter of the silo) , then for a given time t (in hours),

$$GDt = \sigma L\pi D^2/4$$

or

$$L = GDt/(\sigma\tau D^2/4)$$

Substituting G = 1600 kg/(m-hr), D = 25 m, $\sigma = 1600$ kg/m^3,

$$L = 0.05t \quad \text{(L in meters, t in hours).}$$

According to this finding, it would take approximately 20 hours of constant tornadic winds to remove a one meter depth of material from the silo. This analysis is also useful to assess the transport of friable bentonite clay; however, appropriate particle sizes and density must be used. Provided the bentonite clay cap remains moist, transport of the clay or the confined residue by wind entrainment is unlikely.

5.0 Bentonite Clay as a Radon Barrier

The Bechtel report [2] discussing the amount of bentonite clay required to effectively reduce radon gas emission into the silo head space has been reviewed. The following conclusions and observations are offered.

(1) The report uses a diffusion coefficient that is somewhat larger than that of radon in pure water, thus their calculation of the effectiveness of the bentonite cap is a conservative underestimate.

(2) While the Bechtel calculations where not checked in detail a simple diffusion transport calculation was performed. Our calculation confirms that a foot of bentonite clay should effectively eliminate radon emissions into the head space, provided diffusion is the dominant transport mechanism.

(3) The model proposed in the Bechtel report may be overly simplistic. Over time there are a number of mechanisms which could alter the effectiveness of the barrier.

(a) Exposure to strong acids, bases, or floride containing fluids may break down the bentonite. The absence of these agents should be assured.

(b) If the radium in the residue is mobile (i.e. dissolved), it might diffuse upward, thus providing a source of radon gas near the top of the bentonite cap, reducing the effectiveness of the barrier.

(c) If the pore fluid in the residue is saline or if the residue contains soluble salts, water may be drawn out of the bentonite causing it to shrink and possibly crack, again reducing its effectiveness.

(d) If pores in the residue are not already filled with fluid, then some of the moisture in the bentonite slurry will drain into the residue. This drainage would be exacerbated if the clays are flocculated by the diffusion of salts from the residue into the cap.

(e) If any gas-producing reactions occur in the K-65 wastes, or as a result of bentonite-residue interactions, a gas bubble could form beneath the bentonite cap. Such a gas bubble might eventually breach the bentonite layer. In view of the activity contained in these tanks, one likely mechanism for gas production is water radiolysis. In a confined space this could produce an explosive mixture of hydrogen and oxygen gas. An approximate calculation indicates that between 1000 and 2000 liters of explosive hydrogen - oxygen mixture could be produced per tank in a year.

(f) Compaction of the K-65 residue may cause pore fluid migration. If this fluid were to collect at the bentonite residue interface it could, over time breach the overlaying clay barrier.

In summary, this review concludes that the proposed one foot thick bentonite layer will effectively eliminate the diffusion of radon gas into the head space. However, without detailed knowledge of the K-65 residue chemistry, we feel it is important to raise the above concerns regarding possible chemical interactions between the bentonite and the residue. It was not clear from the information available whether these or other similar concerns had been addressed. As stated in the Bechtel study of the K-65 silos[2], the use of a "free -flowing" material to cover the residue is "conceptual in nature, and studies will be required to evaluate their feasibility and cost." The subsequent calculation by Bechtel establishes the amount of bentonite that would be required but does not fully demonstrate its feasibility.

6.0 Review of the K-65 PRA

6.1 Observations on Severe Weather (Tornado) Risk Assessment

In the PRA for the silos at the Feed Materials Production Center, a risk assessment was performed for severe weather winds. However, this risk assessment considered only tornadoes and their affect on the silos in question. This was a complete risk assessment in the sense that all levels of tornado intensities were considered and the effects on the structures of these different intensity tornadoes were considered. A brief review of the tornado risk assessment was made, resulting in the following observations:

Observation 1. Experience shows that, for low wind velocities, the probability of sustained high winds not associated with tornadoes is usually higher than the corresponding probability of tornado-induced winds . Thus, in general, in doing a risk assessment of the effects of wind on a site, the effects of sustained winds and tornadoes must be considered separately. No direct consideration of sustained winds was included in this risk assessment.

Observation 2. The tornado risk assessment was based on the analysis of tornadoes occurring in Ohio during a nine year period (1980-1989). During this period, 117 tornadoes occurred over Ohio. For an analysis of this sort, this time period is relatively short and generally inadequate for an accurate assessment of tornado occurrence frequencies. In addition, since the site is very near the Indiana border, tornadoes in Indiana should have been included in the analysis. To estimate the impact of using this limited data set, tornado catalogs from three different sources were examined for the region in question. From [10], a tornado occurrence frequency of 4.12E-04/sq mile/yr was determined. From Reference [11], a corresponding occurrence frequency of 5.18E-04/sq mile/year was determined. Finally, data from the National Severe Storms Forecast Center [12], was used to obtain an occurrence rate of 8.2E-04/sq mile/year. All of these occurrence frequency estimates were based on a significantly greater number of tornadoes than considered in the K-65 PRA. The PRA estimated an occurrence frequency of 1.25E-04/sq mile/year. It should also be noted that the last estimate (from [12]) was based on the finest discretization, and could perhaps be considered the most accurate. Hence, it is felt that the occurrence frequency estimated in the PRA is low by a factor of 4 to 8. It should be noted that the final risk estimates are directly proportional to the occurrence frequency assumed.

Observation 3. The methodology used to assess the probability of exceedance (per year) for each tornado intensity is somewhat less than the current state-of-the-art. A state-of-the-art analysis would include the following elements:

a. Variation of tornado intensity with occurrence (Tornado occurrences decrease rapidly with increased intensity),

b. Correlation of width and length of damage area (longer tornadoes are usually wider),

c. Correlation of area and intensity (stronger tornadoes are usually larger than weaker tornadoes),

d. Variation in tornado intensity along the damage path length (tornado intensity varies throughout its life cycle), and

e. Variation of tornado intensity across the tornado width path.

A model incorporating all these effects and based on a large number of tornadoes is given in Reinhold and Ellingwood, [13] Figure 5 presents a comparison of the annual probabilities of exceedance of different wind velocities as derived in the K-65 PRA report and as derived by the methodology of Reinhold and Ellingwood. It can be seen that the probability of exceedance at low velocities has been very conservatively estimated in the K-65 PRA whereas the probability of larger wind velocities has been underestimated.

Summary As stated in the PRA, wind speeds of 112 miles per hour are considered sufficient to fail the dome of the silos and it is assumed that such failure releases a significant quantity of radionuclide inventory. Although during this brief review it was not possible to trace the impact of the differing wind speed frequencies on public risk, it seems likely that the overall impact of winds has been somewhat overestimated for low wind velocities and underestimated for larger wind velocities associated with tornadoes. Since, according to Table 2.5 of the K-65 PRA, the largest contributor to risk is associated with the lower wind speeds, it is likely that the overall risk due to tornadoes has not been underestimated.

6.2 Observations on the Seismic Assessment.

In the K-65 PRA report, only three pages were devoted to seismic activity and its potential impacts on the site hazard to the public. A seismic probabilistic assessment was not performed, although a review of the local earthquake activity was made. In addition, the impact of a 0.05g earthquake on the silos was evaluated using a linear structural analysis. Based on a brief review of this material, the following observations can be made:

Observation 1. The seismic analysis was not a risk assessment in the sense that only one (very low) earthquake level was considered.

Observation 2. From a seismic risk assessment viewpoint, consideration of only a 0.05g earthquake is inadequate, as experience with a large number of seismic probabilistic risk assessments has shown that for the eastern and central United States higher earthquake levels dominate the computed risks. In general, the analysis should have considered a full spectrum of earthquake-induced accelerations from 0.05g up to at least 0.75g. Furthermore, from the quoted stresses resulting from the structural analysis at 0.05g, it is likely that significant cracking and spalling would occur at an earthquake level of 0.10g, which again would be expected to have a relatively high level of occurrence. Thus, larger earthquakes are likely to be the dominant risk contributors.

Observation 3. Although the details of the seismic structural analysis were not reviewed, it is strongly suspected that the following aspects were not included in the analysis:

a. Local site amplification due to the nature of the soil site.

b. Reduction of the natural frequency of the structures due to degraded concrete material properties, existing cracking, and existing loss of post tensioning.

c. Vertical motion and the induced bending stresses in the dome. In general, vertical motion and accelerations associated with an earthquake are, on the average, 2/3 of that in the horizontal directions.

d. Separation between the wall and the berm due to compaction of the berm and/or berm soil failure. Separation here could result in increased amplified motion in the walls and the dome of the silo.

e. Increase in internal pressure due to vertical motion or "sloshing" during an earthquake which would result from the motion of the cohesionless material stored in the silo.

Each of these effects will increase the computed stresses in the seismic structural analysis.

<u>Summary</u> Based on the above observations, it is suspected that the likelihood of seismically-induced failure of the silos is significant, that the contribution of seismic events to the overall site hazard to the public is significant, and that a detailed risk assessment should have been performed.

7.0 Conclusions/Recommendations

Having been charged with the review of a large quantity of information related to a very complex remediation plan, we have tried to make responsible suggestions and raise appropriate questions. Some or all of these concerns may have already been addressed. However, their resolution was not apparent during our review.

We summarize with a list of conclusions which are qualified by what we feel are outstanding questions.

7.1 Conclusions/Recommendations

It is our opinion that the silo domes will probably fail during a tornado but that the dome will not be removed.

It would take approximately 20 hours of sustained tornadic winds to remove 1 meter of friable material from the top of a silo which has had its dome completely remove. The layer of moist bentonite clay being proposed would provide significant protection against dispersal of residue.

The installation of one foot of bentonite over the top of the residue in silos 1 and 2 will effectively eliminate the diffusion of radon into the head space.

The PRA did not properly treat all aspects of wind and earthquake risk. For detailed discussion of specific concerns see section 6.0 of this report.

Finally, we recommend the installation of a protective structure over the silos. We find no compelling technical reason for making this structure tornado resistant. The purpose of this structure would be to protect the domes from weathering and to protect the side walls from water running off the dome and into the berm. Sampling the air inside the structure would provide a means of measuring the radon emitted through cracks in the side wall and up through the berm. Further, if the domes were to fail spontaneously, this structure would protect the bentonite and silo contents from the weather until corrective action could be taken. The structure should be designed to minimize its impact on final material removal plans.

As we discussed with you during our visit, there is considerable public concern regarding the safety of the silos. This structure would be a visible sign of the remediation effort.

7.2 Outstanding Questions

Are there chemical agents in the residue that could attack the bentonite clay? Of specific concern is the dewatering of the clay by exposure to salts.

Is there a potential for producing gasses other than radon which may accumulate beneath the bentonite layer? Could the production of hydrogen and oxygen through water radiolysis be a potential hazard?

Will the head space be monitored to evaluate the integrity of the bentonite layer?

What are the factors contributing to the poor condition of silos 1 and 2 compared to silos 3 and 4? One obvious difference is their contents. Silos 1 and 2 contain residue that is 30 to 40 percent water.

Camargo described silos 1 and 2 as being in poor condition while silos 3 and 4 were described as being in good condition. Yet, Bechtel uses arguments of similarity between the four tanks in order to justify using the concrete properties of silo 4 samples to analyze silos 1 and 2. Is there information obtained since the Camargo study which suggests that the condition of tanks are more comparable than originally thought? Again the concern is not the failure of the domes. Even using silo 4 concrete strength, which is the best that could be expected for silos 1 and 2, the domes are in serious danger of failure. Our concern is that other accident scenarios may have been eliminated based on analyses performed with optimistic estimates of concrete strength.

Have the issues of seismic response been properly and completely addressed? We can not conclude that they have. Slope and foundation stability were not addressed, as pointed out by Camargo. Further, Camargo did not have actual concrete properties and assumed 3000 psi concrete for the base slab and silo walls. The actual values from silo 4 (one of the "good" ones) suggests a maximum of 1300 psi. The effect of this difference should be addressed and the Camargo analysis should be reviewed in detail.

Questions regarding the determination of wind and earthquake magnitudes are discussed in section 6.0 of this report.

8.0 References

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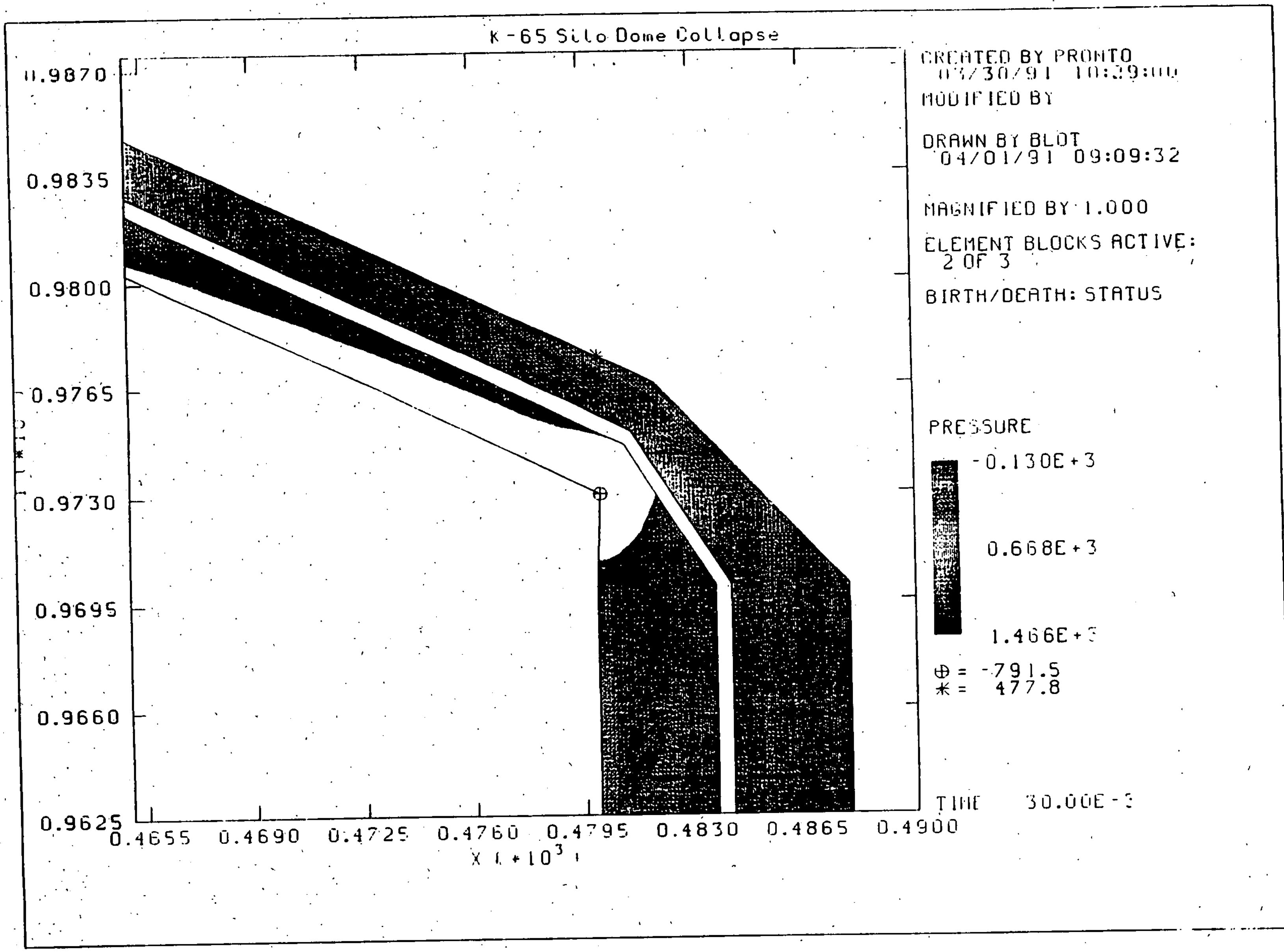

K-65 Silo Dome Collapse
CREATED BY PRONTO
MODIFIED BY
DRAWN BY BLOT
04/01/91 09:09:32
MAGNIFIED BY 1.000
ELEMENT BLOCKS ACTIVE:
2 OF 3
BIRTH/DEATH: STATUS
PRESSURE
-0.130E+3
0.668E+3
⊕ = -791.5
✳ = 477.8
0.9870
0.9835
0.9800
0.9765
0.9730
0.9695
0.9660
0.9625
0.4655
0.4690
0.4725
0.4760
0.4795
0.4830
0.4865
0.4900
X (*10^3)

FIGURE 1

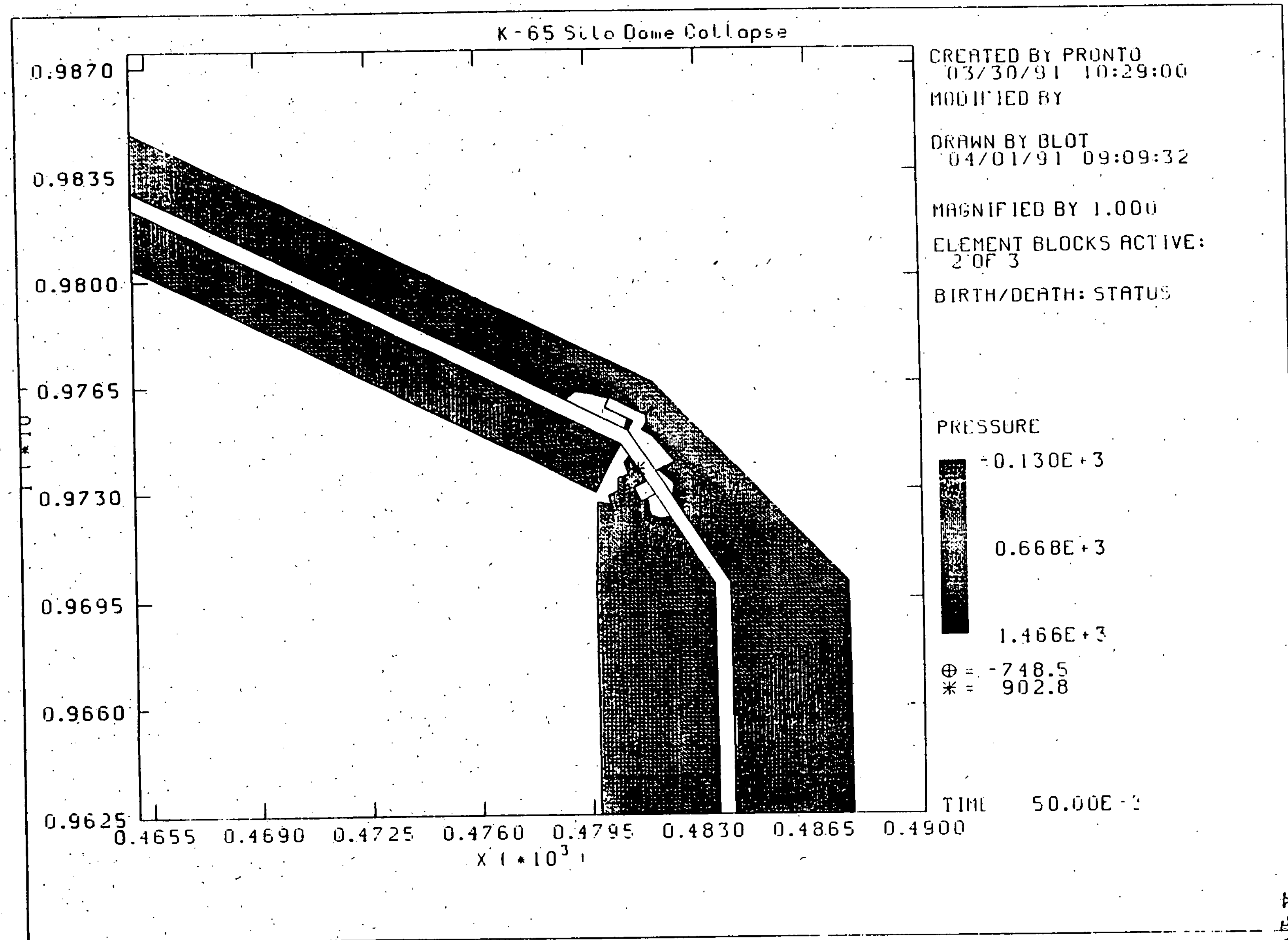

K-65 Silo Dome Collapse
CREATED BY PRONTO
03/30/91 10:29:00
MODIFIED BY
DRAWN BY BLOT
04/01/91 09:09:32
MAGNIFIED BY 1.000
ELEMENT BLOCKS ACTIVE:
2 OF 3
BIRTH/DEATH: STATUS
PRESSURE
-0.130E+3
0.668E+3
1.466E+3
⊕ = -748.5
* = 902.8
TIME 50.00E-3
0.9870
0.9835
0.9800
0.9765
0.9730
0.9695
0.9660
0.9625
0.4655 0.4690 0.4725 0.4760 0.4795 0.4830 0.4865 0.4900
X (*10^3)

FIGURE 2

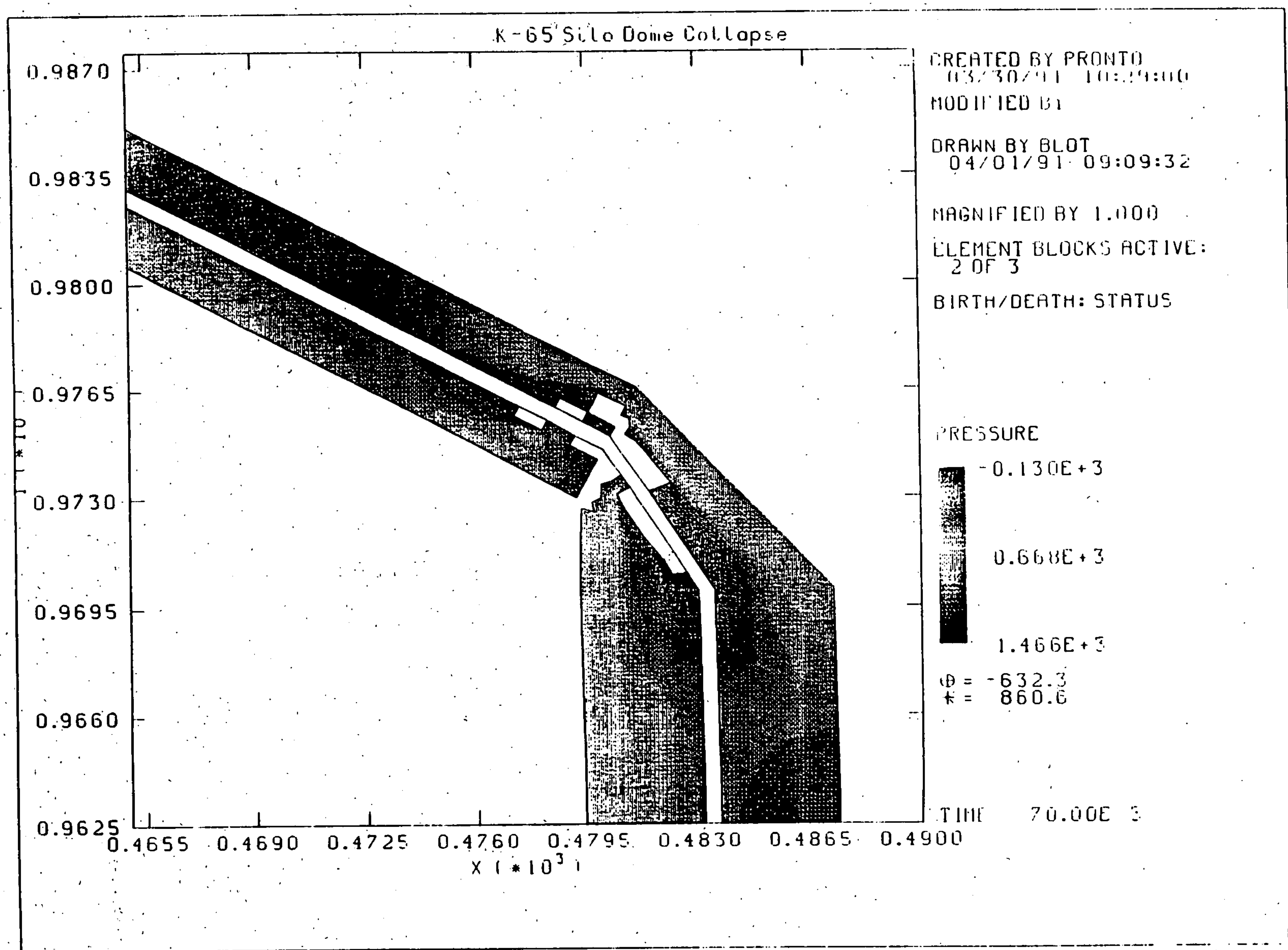
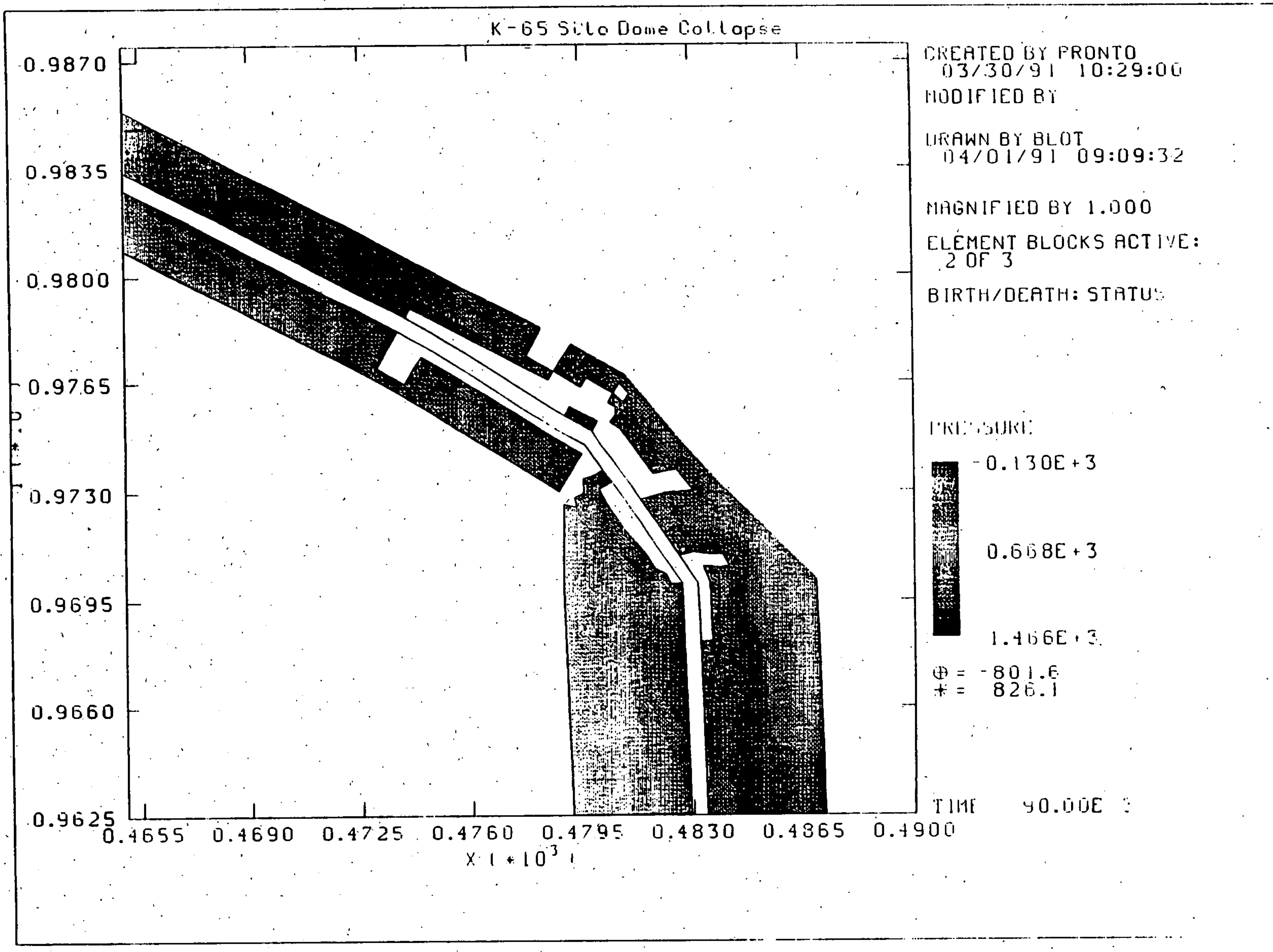

K-65 Silo Dome Collapse
CREATED BY PRONTO
DRAWN BY BLOT
04/01/91 09:09:32
MAGNIFIED BY 1.000
ELEMENT BLOCKS ACTIVE:
2 OF 3
BIRTH/DEATH: STATUS
PRESSURE
-0.130E+3
0.668E+3
1.466E+3
= -632.3
= 860.6
TIME 70.00E 3
0.9870
0.9835
0.9800
0.9765
0.9730
0.9695
0.9660
0.9625
0.4655 0.4690 0.4725 0.4760 0.4795 0.4830 0.4865 0.4900
X (*10³)

FIGURE 3


K-65 Silo Dome Collapse
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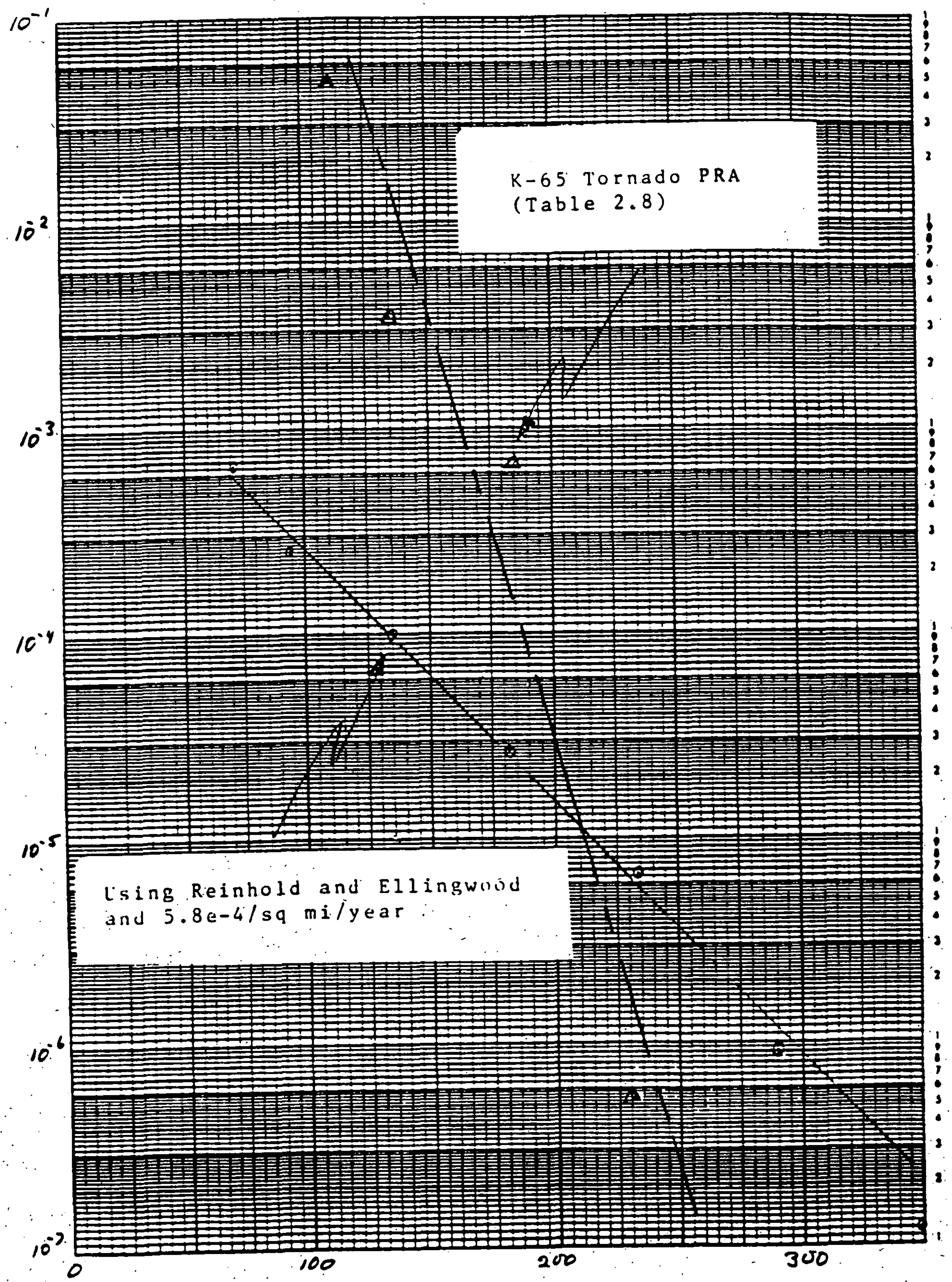
03/30/91 10:29:00
MODIFIED BY
DRAWN BY BLOT
04/01/91 09:09:32
MAGNIFIED BY 1.000
ELEMENT BLOCKS ACTIVE:
2 OF 3
BIRTH/DEATH: STATUS
PRESSURE
-0.130E+3
0.668E+3
1.466E+3
⊕ = -801.6
∗ = 826.1
TIME 90.00E
0.9870
0.9835
0.9800
0.9765
0.9730
0.9695
0.9660
0.9625
0.4655 0.4690 0.4725 0.4760 0.4795 0.4830 0.4865 0.4900
X (*10³)

FIGURE 4

FIGURE 5



K-65 Tornado PRA
(Table 2.8)
Using Reinhold and Ellingwood
and 5.8e-4/sq mi/year
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
100
200
300